Organized Excitons

Macroscopically Ordered Electronic State Observed

As reported in the August 15, 2002 issue of *Nature*, Leonid Butov and Daniel Chemla of Berkeley Lab's Materials Sciences Division, in collaboration with Arthur Gossard at the University of California Santa Barbara (UCSB), have observed a new macroscopically ordered exciton state in a specifically designed semiconductor nanostructure. This state, ordered over distances that can reach one millimeter, is indicative of the formation of a new exciton condensate.

Excitons can be created by laser excitation of a semiconductor. They are formed by the pairing of a negatively charged electron and a positively charged "hole," analogous to the pairing of an electron and proton to form a hydrogen atom. Since the 1960's it has been predicted that excitons could form a quantum liquid, or even a Bose-Einstein condensate in the solid-state. This has, however, never been verified experimentally because in "normal" semiconductors, excitons have a short lifetime and cannot be easily and quickly cooled to the low temperatures required for condensate formation. Further, as hydrogen atoms, which form molecules, excitons attract each other and at high density collapse into an electron-hole plasma.

The Berkeley Lab team approached the challenge by engineering new nanostructures, "coupled quantum wells", able to sustain excitons that are long-lived, cool quickly and repel each other. The very high quality "coupled quantum well" structures are grown at UCSB. These structures consist of two 8-nm-thick layers of GaAs (wells) separated by a 4 nm "barrier" layer of AlGaAs, which has a higher bandgap (see figure). Under appropriate temperature, electrical bias, and laser excitation conditions, stable "indirect" excitons are formed with their electrons in one of the wells and their holes in the other. Because of this spatial separation, their lifetime is considerably increased and they acquire an electric dipole that induces a repulsive interaction. The quantum well structure is embedded in a bulk, three dimensional, semiconductor whereas the excitons are two-dimensional; thus they can move freely through the quantum well plane, but not in the perpendicular direction. Furthermore, the coupling of the 3D-phonons, vibrational quanta of the bulk semiconductor, with the 2D-exciton enhances the cooling rate By using a tightly focused laser to create the excitons and by monitoring their location through the spatially resolved photoluminescence emitted when the exciton electron and hole recombine, their motion parallel to the quantum well plane can be studied.

The results were surprising. At a temperature of 1.8 K, rather than simply randomly diffusing away from the laser spot, the excitons formed a macroscopically ordered state, observed as a bright ring fragmented into a chain of circular spots extending out to a diameter of hundreds of microns (see figure). Increasing the temperature destroyed the delicate ordering of this quantum liquid system, as expected. The ability to work at 1.8 K however, contrasting with the millionth of a degree above absolute zero Kelvin temperature required for the studies of Bose-Einstein condensates observed in atoms, makes the exciton system far more experimentally accessible. In this context, the new observation is an important step toward the creation of Bose-Einstein condensate excitons which will provide scientists with new possibilities for observing and manipulating quantum properties of matter and perhaps developing advanced quantum information devices in the solid state.

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L. V. Butov, A. C. Gossard, and D. S. Chemla, "Macroscopically ordered state in an exciton system," *Nature* **418**, 751 (2002).